DESIGN WINDOWS FOR THIN AND THICK LIQUID PROTECTION SCHEMES IN IFE REACTOR CHAMBERS

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Overview

- **Thin liquid protection schemes (Prometheus)**
  - Major design questions
  - "Wetted wall" concept: low-speed normal injection through a porous surface
  - "Forced film" concept: high-speed tangential injection along a solid surface
- **Thick liquid protection (HYLIFE-II)**
  - Major design questions
  - Turbulent liquid sheets: rectangular or 2D turbulent jets at high density ratio

Thin Liquid Protection

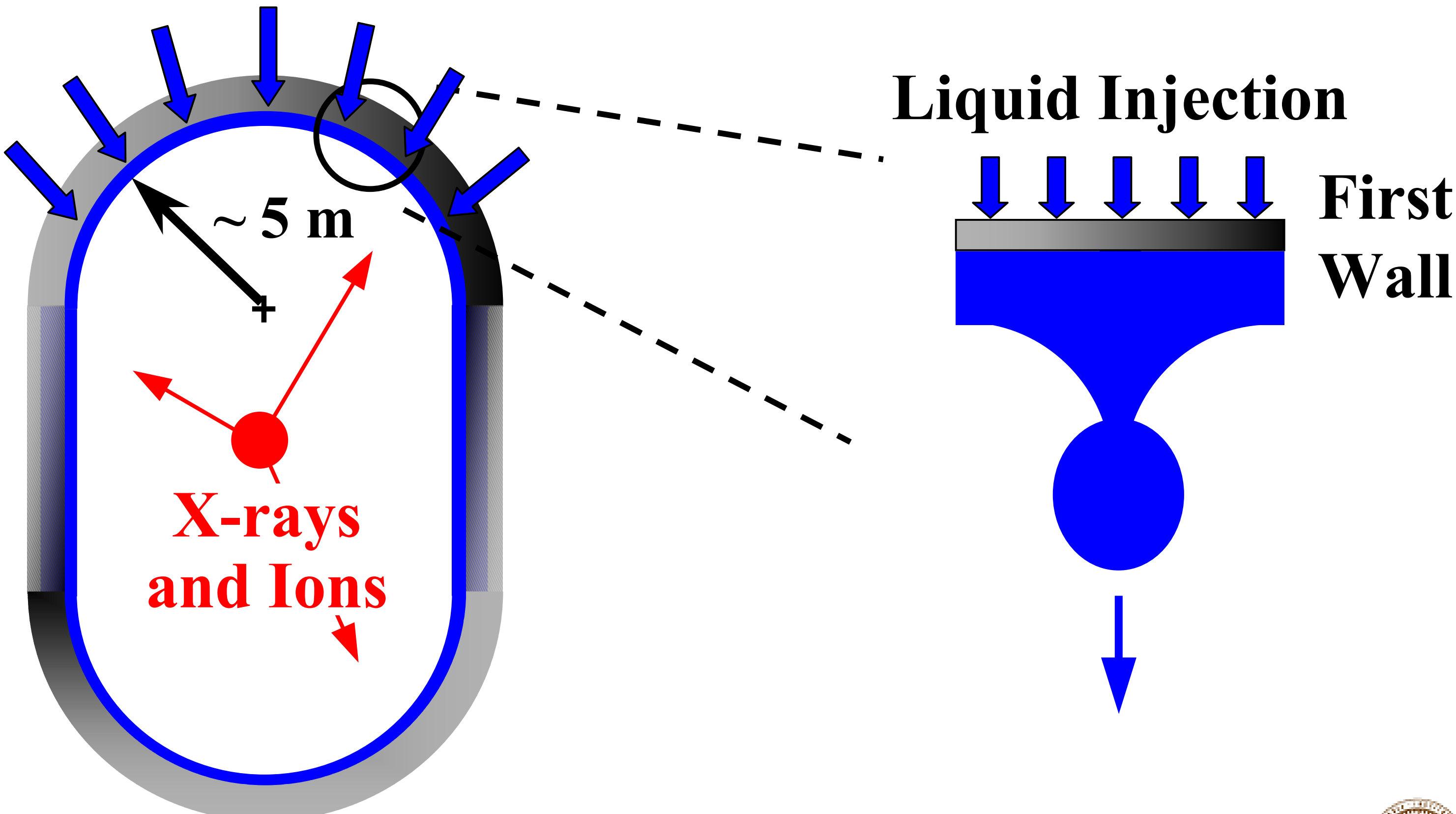
Major Design Questions

- Can a stable liquid film be maintained over the entire surface of the reactor cavity?
- Can the film be re-established over the entire cavity surface prior to the next target explosion?
- Can a minimum film thickness be maintained to provide adequate protection over subsequent target explosions?

Study wetted wall/forced film concepts over "worst case" of downward-facing surfaces

Wetted Wall

- **Prometheus: 0.5 mm thick layer of liquid lead injected normally through porous SiC structure**



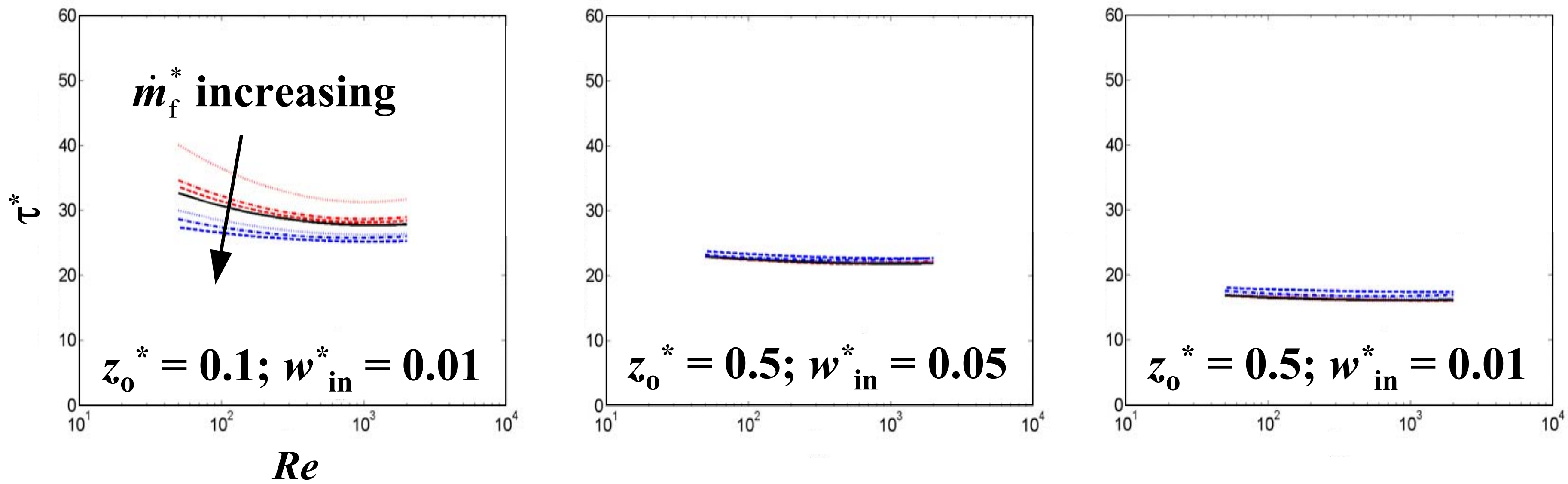
Wetted Wall Parameters

- **Length, velocity and time scales**

$$l = \sqrt{\sigma / [g(\rho_L - \rho_G)]} \qquad U_o = \sqrt{g\,l} \qquad t_o = l / U_o$$

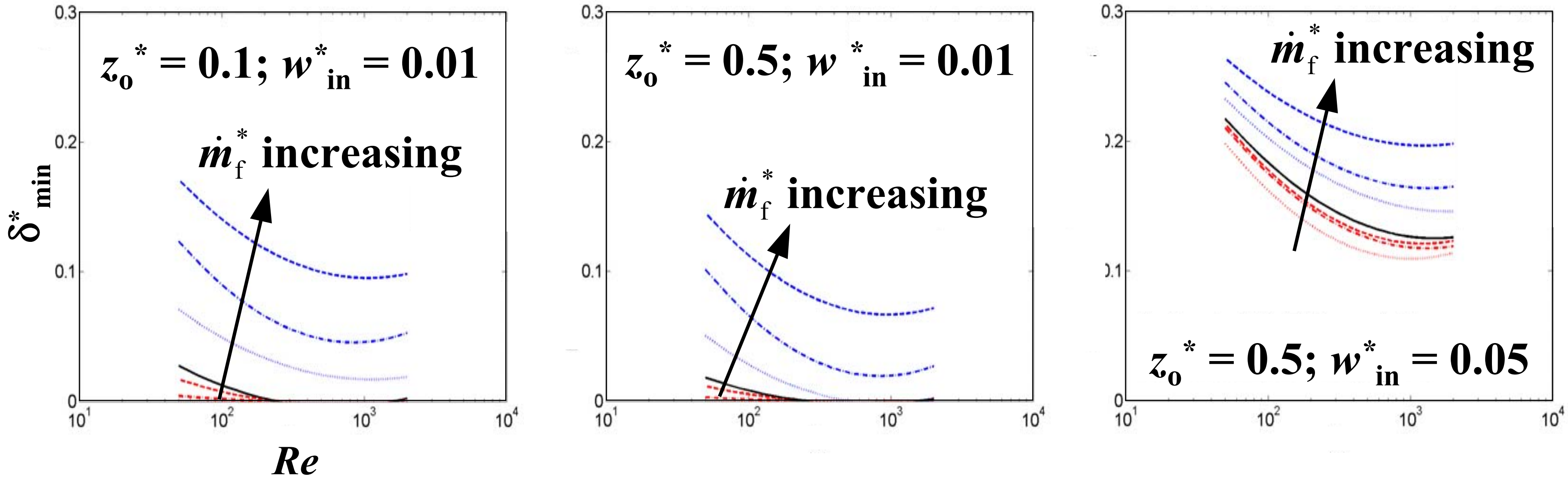
- **Nondim. drop detachment time** $\tau^* \equiv t_d / t_o$
  - Droplet detachment time t_d
- **Nondim. min. film thickness** $\delta^*_{min} \equiv \delta_{min} / l$
  - Minimum film thickness δ_{min}
- **Nondim. initial film thickness** $z^*_o \equiv z_o / l$
  - Initial film thickness z_o
- **Nondim. injection velocity** $w^*_{in} \equiv w_{in} / U_o$
  - Liquid injection velocity w_{in}

Drop Detachment Time



- **Nondim. mass flux**
  $$\dot{m}_f^* = \dot{m}_f / (\rho_L U_o)$$
  - Mass flux $\dot{m}_f$
- **Reynolds number**
  $$Re = U_o l / \nu_L$$

Minimum Film Thickness



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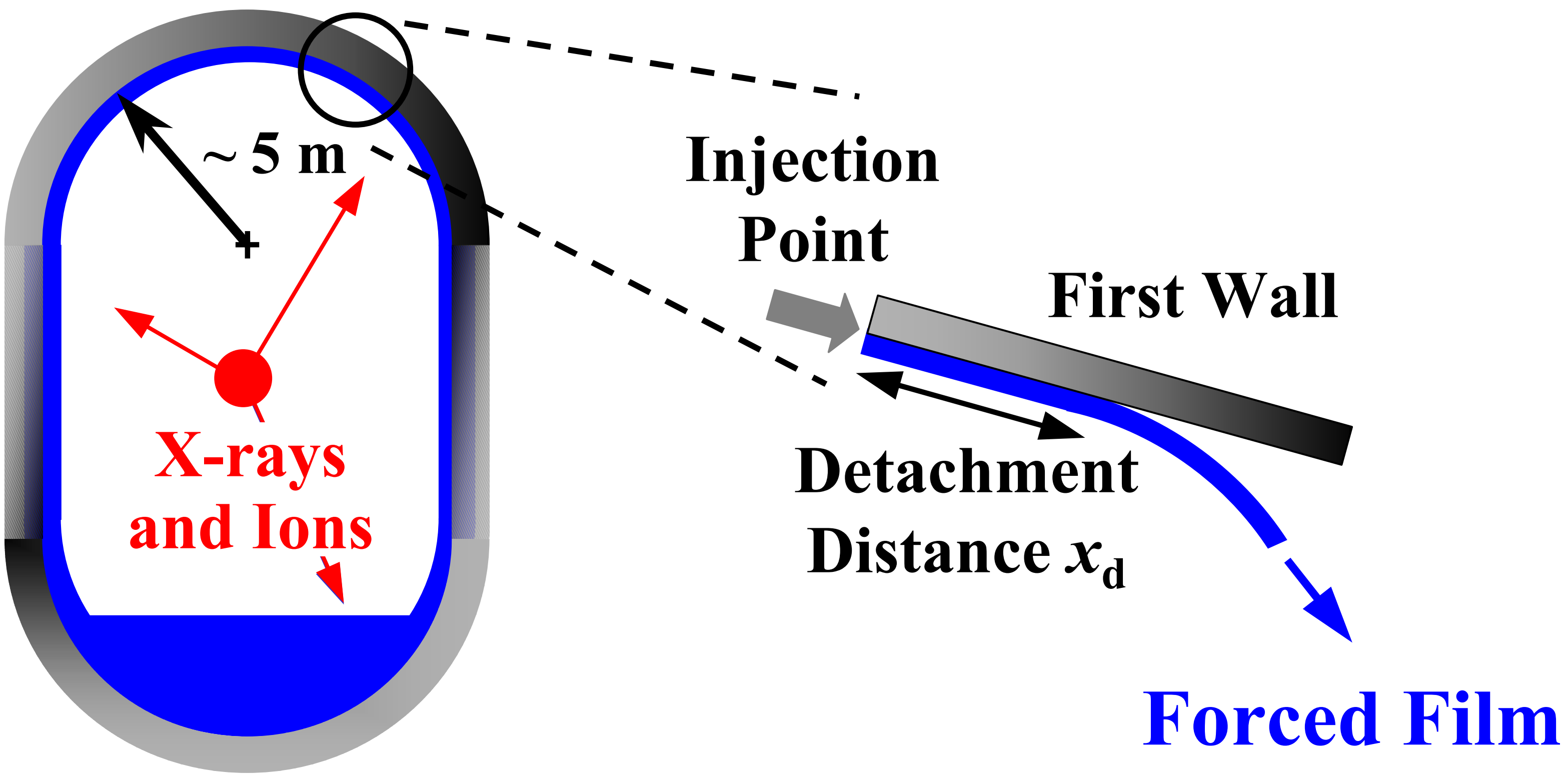
red dotted	$\dot{m}_f^* = -0.005$	blue dotted	$\dot{m}_f^* = 0.005$
red dash-dot	$= -0.002$	blue dash-dot	$= 0.01$
red dashed	$= -0.001$	blue dashed	$= 0.02$
black solid	$= 0$		

Wetted Wall Summary

- **General nondimensional charts applicable to a wide variety of candidate coolants and operating conditions**
- **Stability of liquid film imposes**
  - Lower bound on repetition rate (or upper bound on time between shots) to avoid liquid dripping into reactor cavity between shots
  - Lower bound on liquid injection velocity to maintain minimum film thickness over entire reactor cavity required to provide adequate protection over subsequent fusion events

Forced Film

- **Prometheus: Few mm thick Pb "forced film" injected tangentially at >7 m/s over upper endcap**



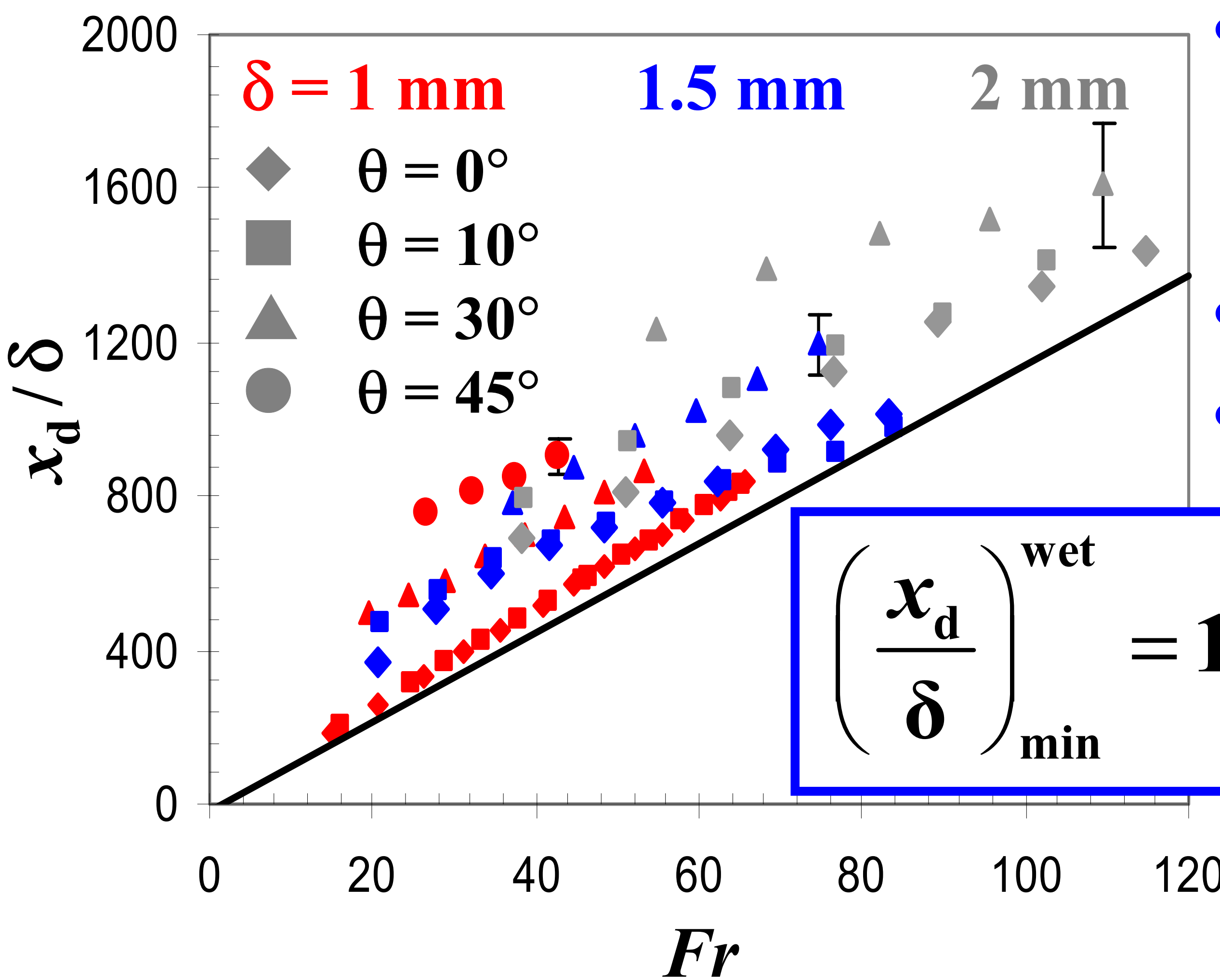
Forced Film Parameters

- **Length scale δ = initial film thickness**
- **Froude number**

$$Fr \equiv \frac{U}{\sqrt{g(\cos\theta)\delta}}$$

  - Mean injection speed U
  - Surface orientation θ (θ = 0° ⇒ horizontal surface)
  - Prometheus: for θ = 0 – 45°; Fr = 100 – 680 over nonwetting surface
- **Nondimensional detachment length x_d / δ**
  - Mean detachment length x_d from injection point
- **Nondimensional lateral extent W / δ**
  - Mean lateral extent W

x_d / δ *vs.* *Fr*: Wetting Surface

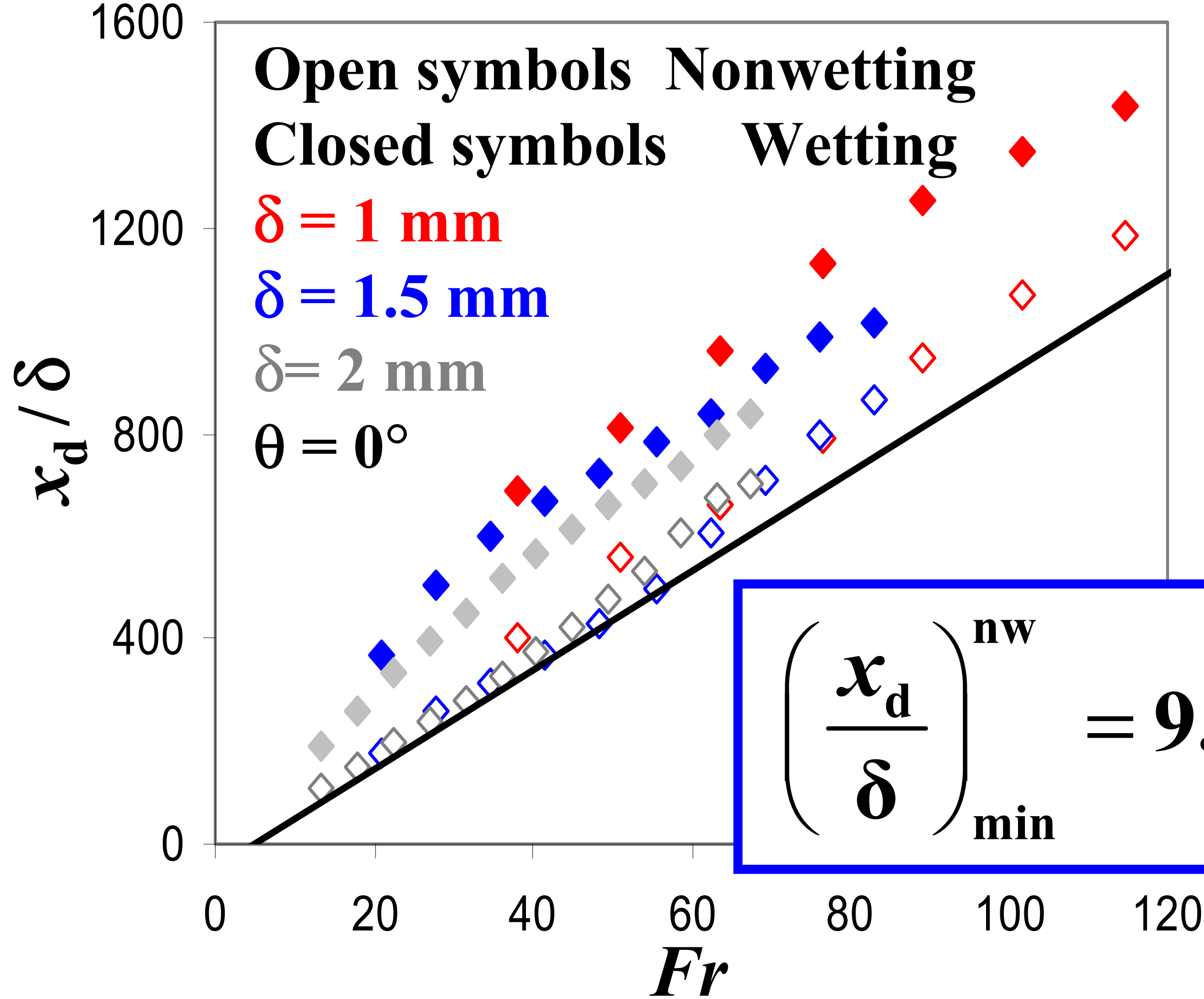


- x_d increases linearly with *Fr*
- x_d↑ as θ↑
- x_d↑ as δ↓

$$\left(\frac{x_d}{\delta}\right)_{min}^{wet} = 11.56\,Fr - 16.1$$

Design Window: Wetting Surface

x_d / δ: Wetting *vs.* Nonwetting



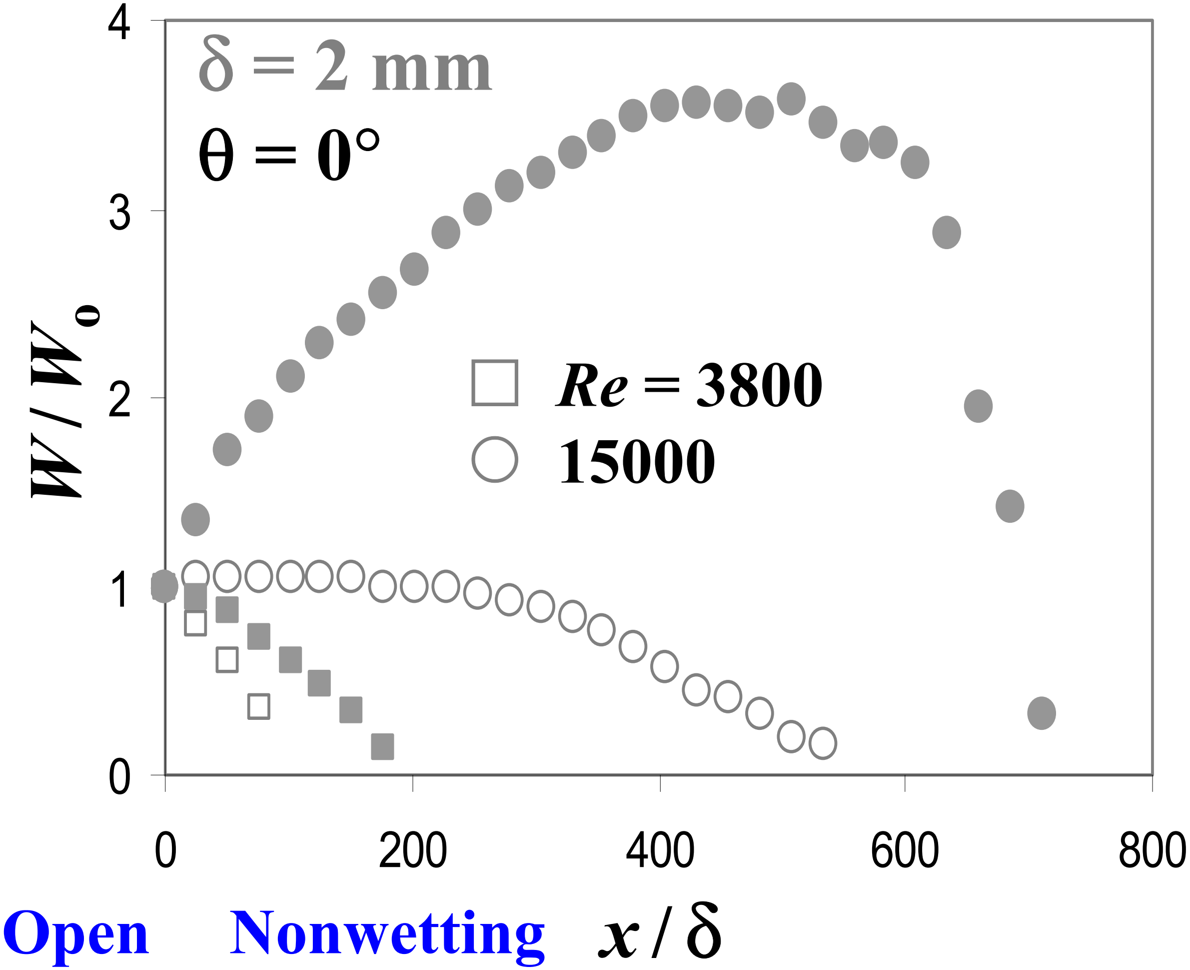
Nonwetting *vs.* Wetting:

- Smaller $x_d \Rightarrow$ conservative estimate
- x_d indep. of δ

$$\left(\frac{x_d}{\delta}\right)_{\min}^{\mathrm{nw}} = 9.62\,Fr - 45.9$$

Design Window

W/W_o: Wetting *vs.* Nonwetting



Open Nonwetting
Closed Wetting

Wetting

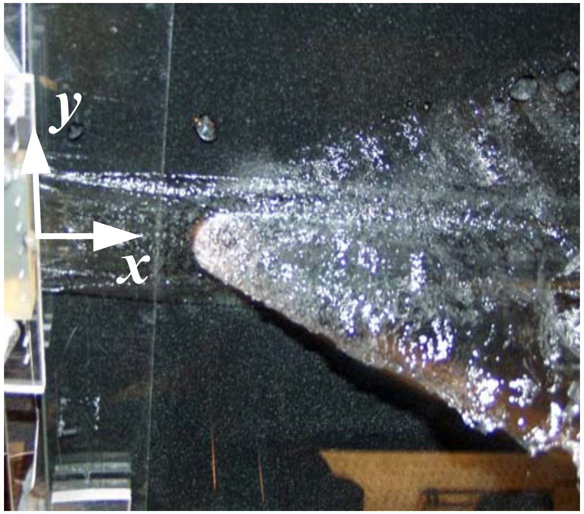
- **Marked lateral growth (3.5×) at higher *Re***

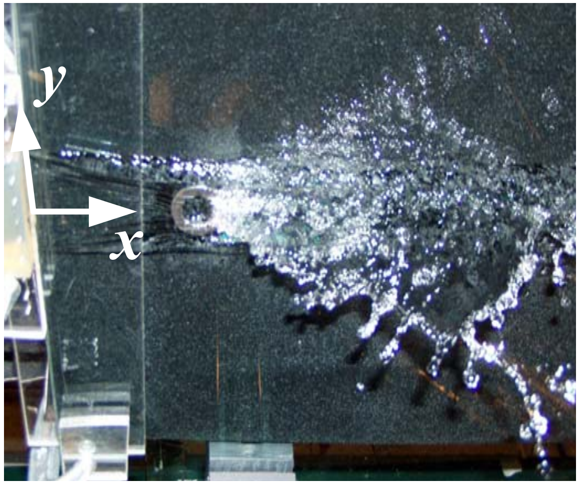
Nonwetting

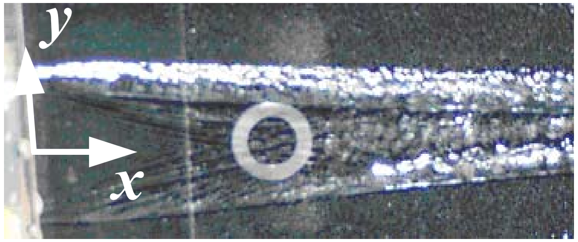
- **Negligible lateral spread**
  - Contact line "pinned" at edges?
- **Contracts farther upstream**

Cylindrical Dams

- **In all cases, cylindrical obstructions modeling protective dams around beam ports incompatible with forced films**
- **Film either detaches from dam, or flows over dam**





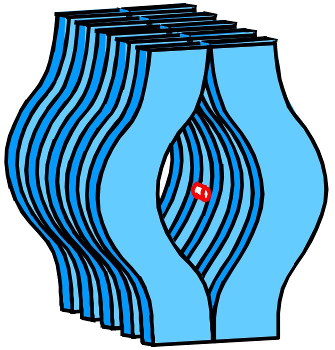


Forced Film Summary

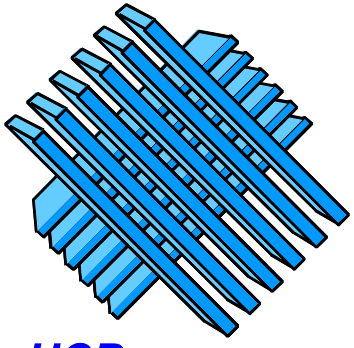
- **Design windows for streamwise (longitudinal) spacing of injection/coolant removal slots to maintain attached protective film**
  - Detachment length increases linearly with Froude number
- **Wetting chamber first wall surface requires fewer injection slots than nonwetting surface ⇒ wetting surface more desirable**
- **Cylindrical protective dams around chamber penetrations incompatible with effective forced film protection**
  - "Aerodynamically tailored" protective dam shapes

Turbulent Liquid Sheets

- **HYLIFE-II: Use slab jets or liquid sheets to shield IFE chamber first walls from neutrons, X-rays and charged particles**



  - Oscillating sheets create protective pocket to shield chamber side walls



  - Lattice of stationary sheets shield front/back walls while allowing beam propagation and target injection

Pictures courtesy P.F. Peterson, UCB

Thick Liquid Protection

Major Design Questions

- Is it possible to create "smooth" prototypical turbulent liquid sheets?
  - 5 mm clearance between driver beam, sheet free surface in protective lattice $\Rightarrow$ > 30 year lifetime for final focus magnets
- Can adjacent sheets, once they collide, separate and re-establish themselves before the next fusion event?
- Can the flow be re-established prior to the next fusion event?
  - Chamber clearing

Liquid Sheets Parameters

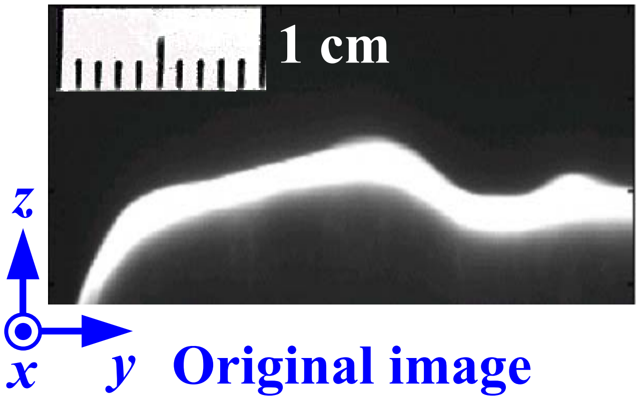
- **Length scale δ = initial sheet thickness Velocity scale U_o = mean speed at nozzle**
- **Reynolds number**
  - HYLIFE-II: $Re \approx 200{,}000$

$$Re \equiv U_o \delta / \nu_L$$

- **Nondimensional distance downstream of nozzle x / δ**
  - Measured from nozzle
  - HYLIFE-II: $x / \delta < 30$ over protective pocket
- **Nozzle dimensions $W_o \times \delta$**
  - $W_o = 10$ cm; $\delta = 1$ cm $\Rightarrow$ aspect ratio $AR = 10$

Surface Ripple Measurements

- **Free surface ⇒ interface between fluorescing water and air**
  - Planar laser-induced fluorescence (PLIF)
- **Free surface found w/edge detection**
  - Threshold individual images
- **σ_z = standard deviation of free surface *z*-position spatially averaged over central 7.5 cm of flow**



Original image

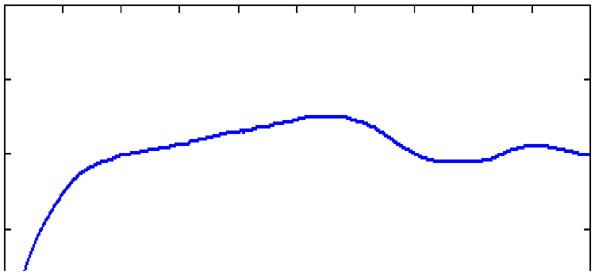
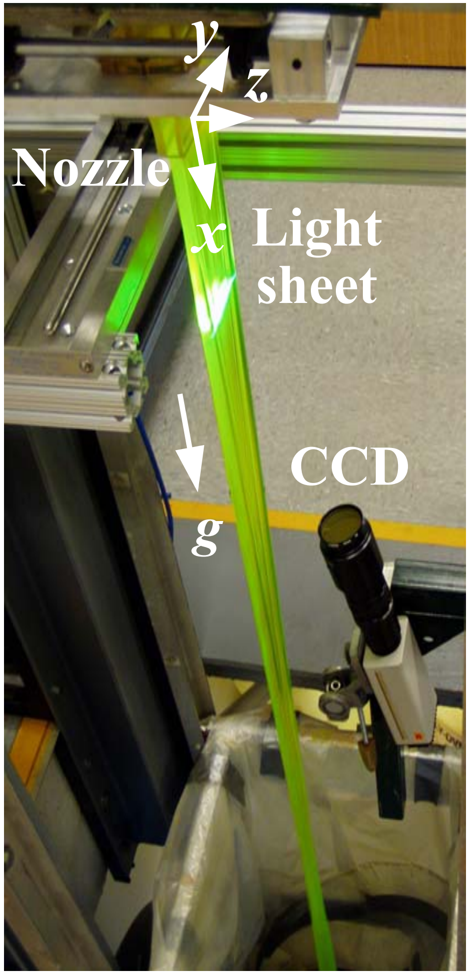
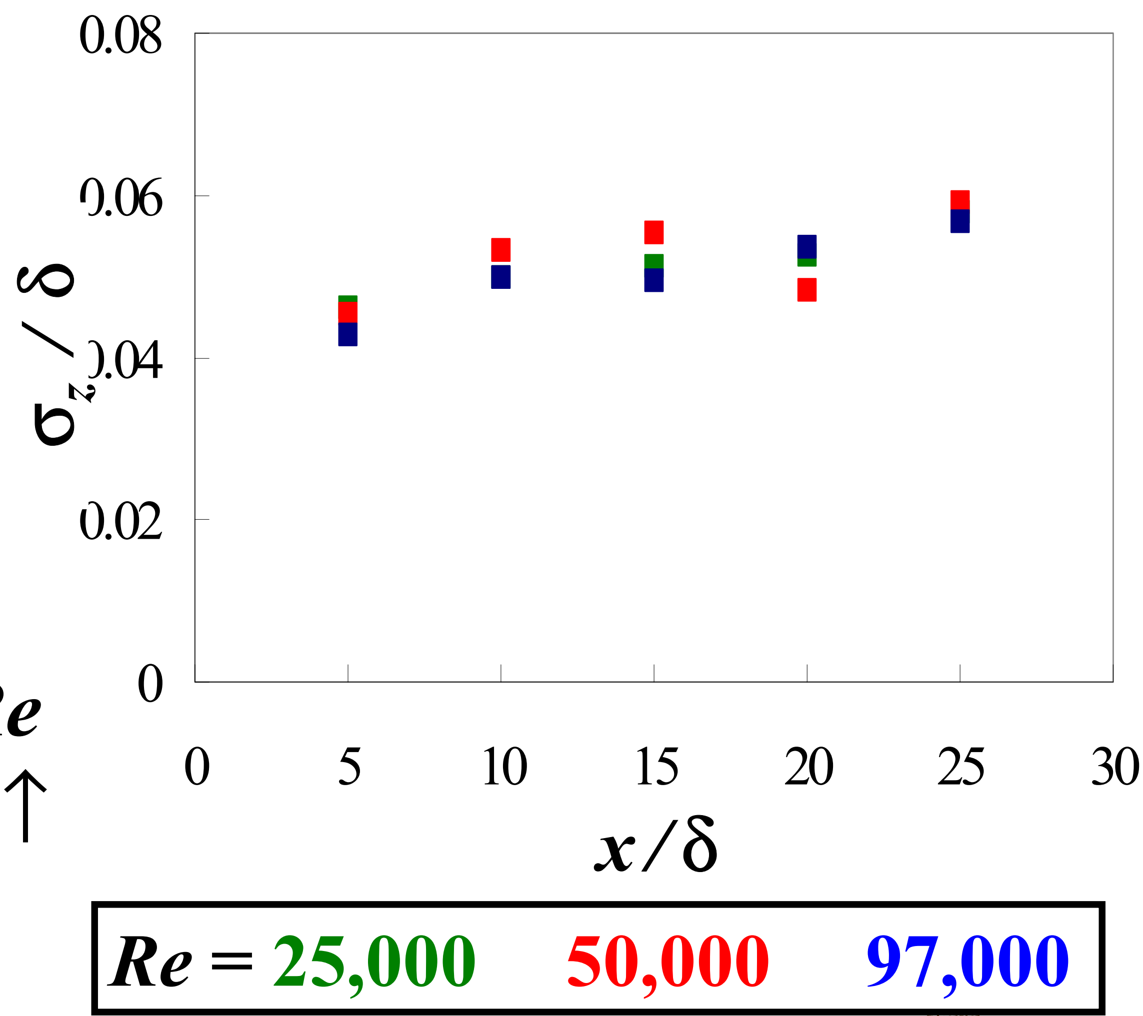


Image after thresholding, edge detection



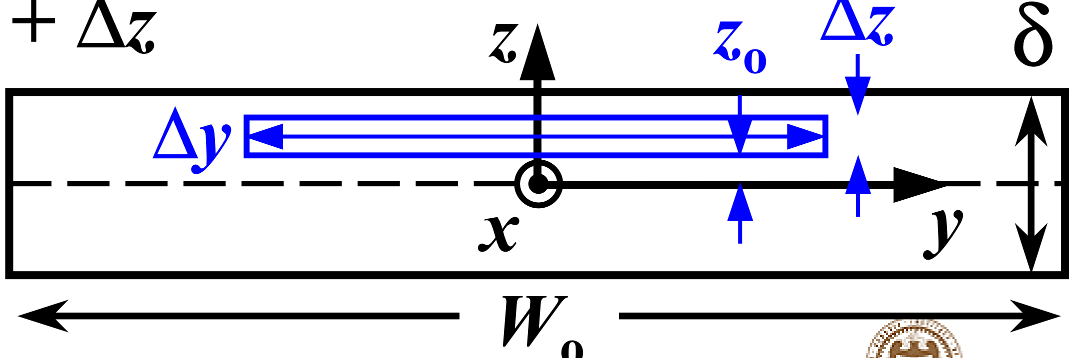
Surface Ripple Results

- σ_z measure of average surface ripple
- $\sigma_z / \delta < 6\%$ for $x / \delta < 25$
- σ_z essentially independent of *Re*
- $\sigma_z \uparrow$ slightly as $x \uparrow$

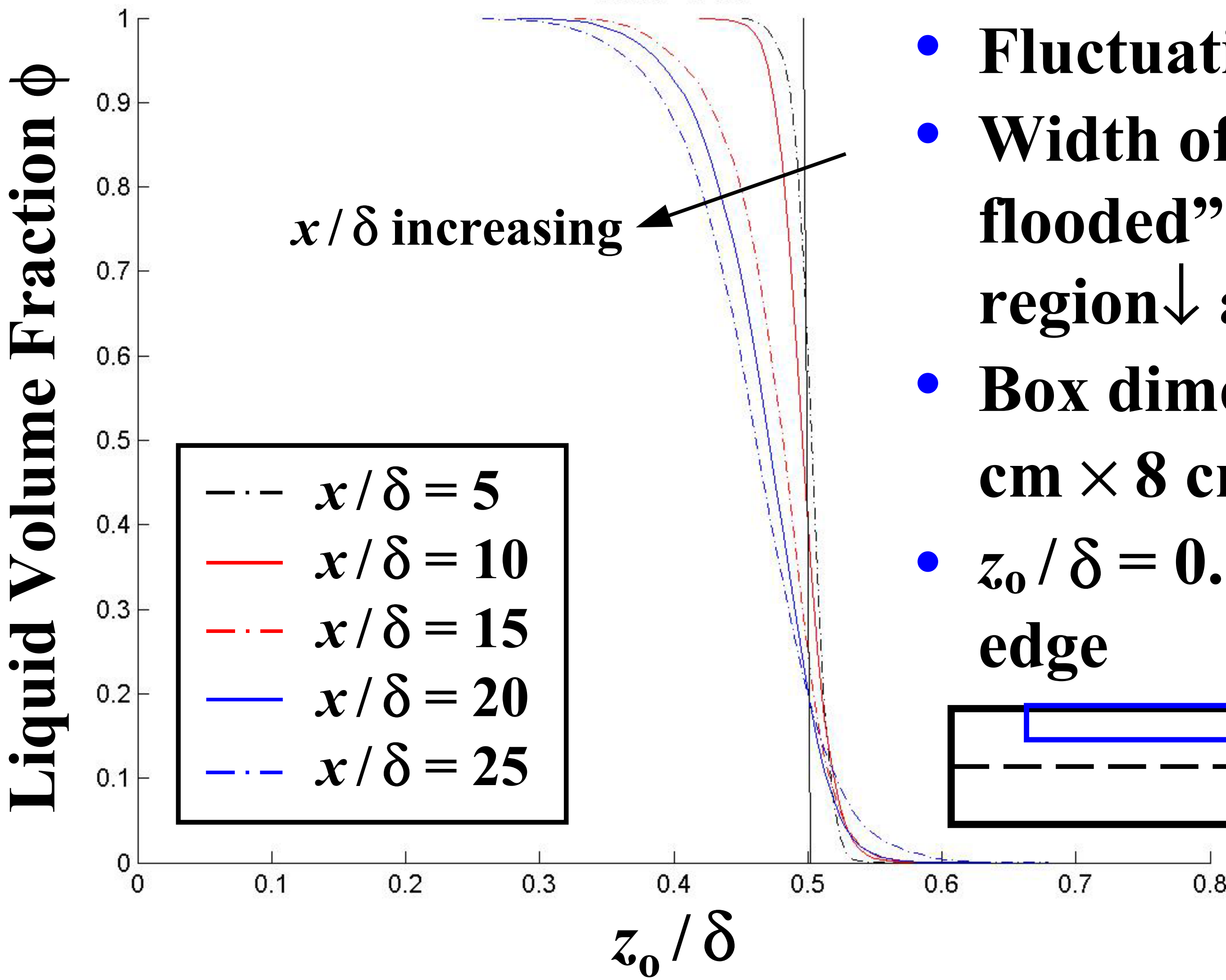


ILASP

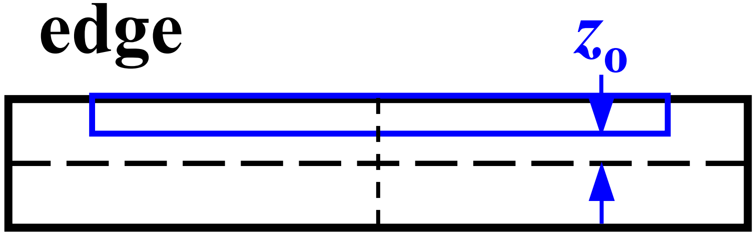
- **Instantaneous liquid area averaged spatial probability (ILASP) = liquid volume fraction ϕ within a $\Delta y \times \Delta z$ "box" located at z at given x**
  - Results for box at nozzle edge useful in neutronics calculations
- **Calculate liquid volume fraction in rectangular box at given x location: box spans $-0.5\Delta y \le y \le +0.5\Delta y$; $z_o \le z \le z_o + \Delta z$**
  - $\Delta z / \delta = 0.01$
  - $\Delta y / W_o = 0.8$



ILASP Results: *Re* = 130,000



- **Fluctuations↑ as *x*↑**
- **Width of "fully flooded" ($\phi = 1$) region↓ as *x*↑**
- **Box dimensions 0.01 cm × 8 cm**
- **$z_o / \delta = 0.5 \Rightarrow$ nozzle edge**



Liquid Sheets Summary

- **Results at *Re* half of prototypical values imply HYLIFE-II jets will have average surface ripple (based on standard deviation) < 5 mm ⇒ *Sheets smooth enough to allow close spacing of jets as dictated by magnet shielding requirements***
  - Fluctuations similar for all *Re* studied
  - Design standard 5^{th} order polynomial contraction along *z*-dimension with flow straightener upstream
- **ILASP results useful in neutronics calculations**
- **Minor (2.5% of total cross-section) blockage upstream of nozzle greatly increases surface ripple**